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Ventilation for Comfort and Cooling: The State of the Art

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Introduction

Buildings are one of the most important economic sectors. The global world's annual output of construction is close to US$3000 billion and represents almost one tenth of the global economy (CICA, 2002). In parallel, buildings represent more than 50 per cent of the national capital investment, while the sector employs more than 111 million employees and accounts for almost 7 per cent of total employment, as well as 28 per cent of global industrial employment. As mentioned by CICA (2002), every job in the construction sector generates two new jobs in the global economy; thus, it can be said that the buildings sector is in a direct or indirect way is linked to almost 20 per cent of global employment.

Concerned with the consumption attributed to the building sector, Baris Der Petrossian (2001) has reported that almost one sixth of the world's resources are consumed by the construction sector, which is responsible for almost 70 per cent of sulphur oxide (SO_x) and 50 per cent of carbon dioxide (CO_2) emissions. According to the United Nations Centre for Human Settlements (Habitat) (UNCHS, 1993), buildings use almost 40 per cent of the world's energy, 16 per cent of the world's fresh water and 25 per cent of the world's forest timber.

As a result of intensive energy conservation measures, the specific energy consumption of buildings spent for heating purposes has almost stabilized or decreased, at least in the developed world. On the contrary, the specific energy needs for cooling has increased in a dramatic way, mainly because the increase of family income in developed countries has made the use of these systems highly popular. Recent statistics show that there are more than 240 million air-conditioning units installed worldwide (IIR, 2002), while the refrigeration and air-conditioning sectors consume about 15 per cent of all electricity used worldwide.

The impact of air conditioning on electricity demand is a significant problem since peak electricity loads are increasing continuously; thus, utilities have to build additional plants. In parallel, important environmental problems are associated with the use of air conditioning.

Passive and hybrid cooling techniques involving heat modulation and dissipation methods and systems, particularly convective cooling techniques, can contribute highly to reducing the cooling load of buildings and to improving thermal comfort during the summer season.

Results of recent research projects (Santamouris and Argiriou, 1997; Santamouris, 2004) have improved knowledge on this specific topic, and developed design tools and advanced techniques to better implement ventilative cooling systems.

In fact, ventilation is very important for the building's energy load. According to Liddament and Orme (1998), air change accounts for approximately 36 per cent of the total space conditioning energy and contributes to almost half of heating equipment losses. Techniques using ventilation for cooling have gained increased interest since the early 1980s (Chandra et al, 1982a, 1982b). Extended monitoring has shown that naturally ventilated buildings typically use less than 50 per cent of the corresponding energy consumption of air-conditioned buildings (Kolokotroni et al, 1996a, b). Research and assessments of passive ventilation cooling techniques in Europe (Kolokotroni et al, 2002) have shown that ventilative cooling techniques may contribute highly to reducing the cooling needs of buildings in Europe.

Sizing of ventilation systems for cooling, as well as selection of the more appropriate strategies to follow, depends upon many climatic, technical, operational,

Table 8.1 *Actual and forecast total air-conditioning sales in the world*

(In thousands of units)	1998 Actual	1999 Actual	2000 Actual	2001 Actual	2002 Projected	2003 Forecast	2004 Forecast	2005 Forecast	2006 Forecast
World total	35,188	38,500	41,874	44,834	44,614	46,243	47,975	50,111	52,287
Japan	7270	7121	7791	8367	7546	7479	7344	7459	7450
Asia (excluding Japan)	11,392	11,873	13,897	16,637	16,313	17,705	19,227	20,890	22,705
Middle East	1720	1804	1870	1915	1960	2010	2060	2112	2166
Europe	1731	2472	2709	2734	3002	3157	3318	3489	3670
North America	10,437	12,408	12,322	11,894	12,521	12,522	12,524	12,525	12,525
Central and South America	1588	1665	2109	1939	1866	1906	1973	2043	2114
Africa	511	670	664	758	781	806	833	861	887
Oceania	539	487	512	593	625	659	693	731	770

Source: JARN and JRAIA (2002)

economic and cultural parameters. Existing tools permit accurate evaluation of the expected performance of the various techniques, while combination methods such a multi-criteria analysis may help to optimize the ventilation system (Blondeau et al, 2002).

This chapter aims to present the more recent progress on the field of convective or ventilative cooling. The main scientific knowledge in the field of natural and mechanical ventilative cooling, as well as in the field of thermal comfort, is also discussed.

Cooling buildings: Recent trends

The continuous improvement of living standards, in association with the increased income of major human groups and non-climatic responsive architecture, has contributed highly to increasing the total sales of air conditioners. Based on recent data, there are more than 240 million air-conditioning units installed worldwide (IIR, 2002), while according to a recent study of the International Institution of Refrigeration (IIR, 2002), the refrigeration and air-conditioning sectors consume about 15 per cent of all electricity utilized worldwide.

The total annual sales of air-conditioning equipment is close to US$60 billion, of which US$20.9 billion are spent for room air units, US$15.7 billion for packaged systems, US$6.5 billion for roof-top units and US$12.3 billion for residential heat pumps (IIR, 2002). Such a number represents almost 10 per cent of the car industry's business.

The air-conditioning market is under continuous expansion. In 1998, the total annual sales of the air-conditioning industry was close to 35,188,000 units; in 2000, it increased to 41,874,000 units, increasing further to 44,614,000 units in 2002 (JARN and JRAIA, 2002), with a predicted level of 52,287,000 units in 2006 (see Table 8.1).

The use of air conditioning in the US and Japan is much higher than in Europe. The European Energy Room Air Conditioners (EERAC) study (Adnot, 1999), carried out by the European Economic Community (EEC), has shown that in Europe, the 'penetration rate' of room air conditioners (using 1997 data) is less than 5 per cent in the residential sector and less than 27 per cent in the tertiary sector (see Table 8.2). The penetration rate in the tertiary sector is almost 100 per cent in Japan and 80 per cent in the US, while almost 85 per cent and 65 per cent of the residential buildings in Japan and the US, respectively, have at least one air conditioner correspondingly.

The number of households in the US with central air conditioning has increased from 17.6 million in 1978 to 47.8 in 1997. In parallel, the number of households with room air conditioners has increased during the same period from 25.1 to 25.8 million (see Table 8.3; EIA, 1997). The energy consumption due to air conditioning has increased, during the same period, from 310,000 billion to 420,000 billion British Thermal Units (Btu). In 1997, American households with air conditioners spent almost US$140 per year for air conditioning, while almost 40 per cent used their air conditioners all summer. Because of the increased efficiency of air conditioners, increase in electricity consumption has not followed the rate of penetration of air conditioners.

Table 8.2 *Penetration of room air conditioners in the tertiary and residential sector in the US, Japan and Europe, 1997*

Country	Tertiary	Residential
Japan	100%	85%
US	80%	65%
Europe	< 27%	< 5%

Source: Adnot (1999)

Table 8.3 *Consumption of electricity for air conditioning and associated factors by survey year*

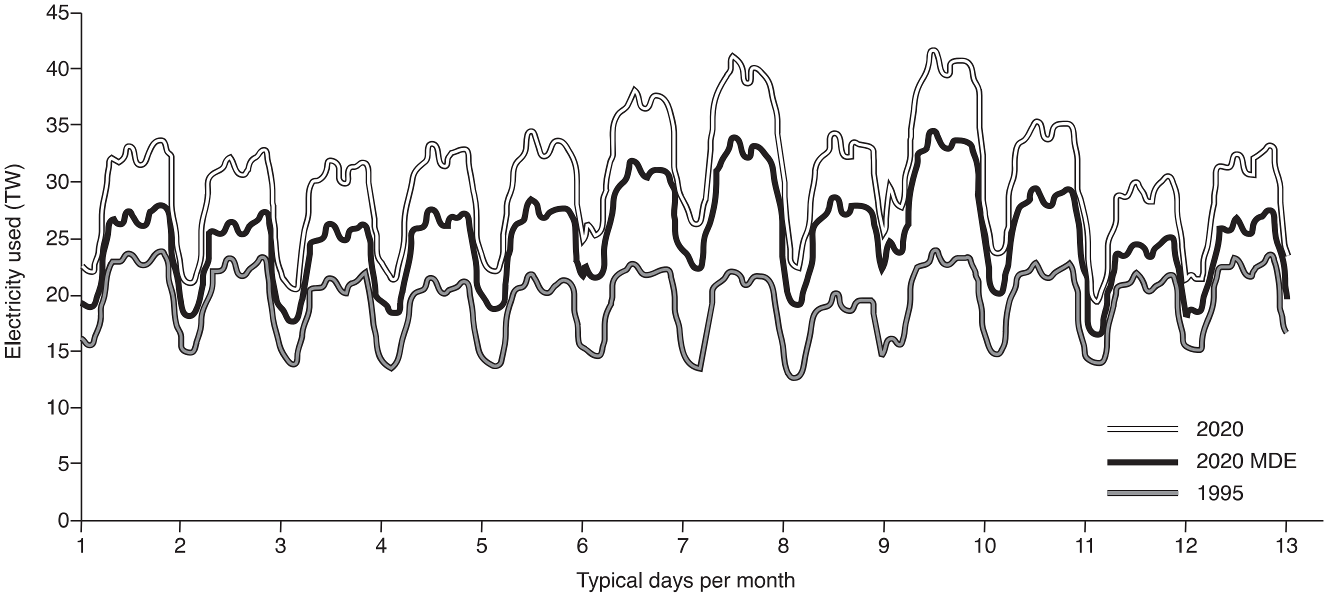
Survey year	Household electricity consumption for air conditioning (billion Btu)	Number of households with central air conditioning (millions)	Number of households with room air conditioning (millions)	Average seasonal energy efficiency ratio (SEER) of central air conditioning units sold during the year
1978	310,000	17.6	25.1	7.34
1980	320,000	22.2	24.5	7.55
1981	330,000	22.4	26.0	7.78
1982	300,000	23.4	25.3	8.31
1984	320,000	25.7	25.8	8.66
1987	440,000	30.7	26.9	8.97
1990	480,000	36.6	27.1	9.31
1993	460,000	42.1	24.1	10.56
1997	420,000	47.8	25.8	10.66

Source: Energy Information Administration (EIA) (1978–1982, 1984, 1987, 1990, 1993, 1997) *Residential Energy Consumption Surveys*

In parallel, the energy consumption for the cooling purposes of the US commercial sector is close to 250TWh (Terawatt hours) per year, while the corresponding peak power demand for summer cooling is close to 109GW.

There are several problems associated with the use of air conditioners. The most important problem deals with the serious increase of peak electricity loads that oblige utilities to build additional plants in order to satisfy demand. As the use of these plants is for a short period, the average cost of electricity increases considerably. In California (Besant-Jones and Tenenbaum, 2001), the demand for electricity during the summer months of 2002 increased due to air-conditioning loads because of the highest temperatures recorded for 106 years. As a consequence, the supply started to fall below demand and electricity prices increased tremendously. It is characteristic that during 1998–1999 and the first months of 2000, the market clearing price in the day-ahead Cal PX (an energy price index in California) was between US$25 and US$50/MWh; it increased to US$150/MWh during the summer months of 2000 (Besant-Jones and Tenenbaum, 2001).

Southern European countries face a very important increase in their peak electricity load, mainly because of



Source: Adnot (1999)

Figure 8.1 *Electricity load curves for 1995 and 2020 in Spain* the very rapid penetration of air conditioning. Because of high demand for air conditioners, Italy faced substantial electricity problems during the summer of 2003. Figure 8.1 depicts the actual load curves, as well as the foreseen evolution of peak electricity load in Spain (Adnot, 1999). It is evident that an extremely high increase of the peak load is expected, which may require doubling of installed power.

In parallel, important environmental problems are associated with the use of air conditioning. Emissions of refrigerant gases used in air-conditioning installations significantly affect ozone depletion and global warming. Refrigeration and air conditioning-related emissions represent almost 64 per cent of all chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) produced (AFEAS, 2001). New air conditioners use more efficient refrigerants that have a lower impact on atmospheric ozone depletion.

Problems related to indoor air contamination should not be neglected as well. Cooling coils and condensate trays can become contaminated with organic dust that may lead to microbial growth. The organic dust may also cause mould and fungal growth in fans and fan housing. Inefficient and dirty filters may also lead to unfiltered air in buildings. Contaminated emissions from cooling towers that have not been properly maintained may cause spread of *Legionella* from poorly maintained systems.

Ventilation for cooling: Basic principles

Ventilation contributes to reducing or eliminating energy for cooling purposes, as well as increasing thermal comfort through two mechanisms:

- by removing the higher-temperature indoor air and replacing it with fresh low-temperature ambient air; and
- by cooling down the human body through the mechanisms of convection, radiation and perspiration.

Fresh air may be introduced to the indoor space through the building openings, (natural ventilation), through the use of fans, (mechanical ventilation) or by a combination of openings and fans (hybrid ventilation).

Cooling of the human body by convection occurs when the surrounding air is cooler than the skin and, thus, heat is carried away from the body. The higher the air speed, the higher is the body cooling effect. According to the existing standards (ASHRAE, 1992; ISO, 1994) permitted air speed should not exceed 0.2m/sec. However, recent research trying to better understand thermal comfort mechanisms in naturally ventilated buildings (Nicol, 2003) has shown that occupants of these buildings may prefer much higher indoor air speeds. Quite recently, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has quantified the difference between the thermal response of people living in air-conditioned and naturally ventilated buildings. A new adaptive comfort standard has been proposed.

In parallel, when ceiling fans are used, air blows downward on the human body; thus, higher speeds are allowed and are supported by the human body. This permits an increase in the indoor air temperature of up to 2° C, which results in very important energy conservation.

When the temperature of the surrounding opaque surfaces in a building is lower than skin temperature, the body is losing heat by radiation. Use of ventilation, especially during the night time, may contribute significantly to reducing the interior temperature of the opaque surfaces of a building. Thus, the radiative balance is negative for the human body, while the interior air reduces its temperature because of the convection between the opaque surfaces and the indoor air.

During hot weather or physical exercise, the human body dissipates excess heat through perspiration mechanisms. When air flows around the skin, it contributes to evaporation of human moisture and, thus, to benefits from the associated latent heat.

Natural ventilation is caused by naturally produced pressure differences due to wind, temperature difference or both. Natural ventilation is achieved by allowing air to flow in and out of a building by opening windows and doors or specific ventilation components such as chimneys. The effectiveness of natural ventilation depends upon the wind speed, temperature difference, size and characteristics of the openings and their orientation to the prevailing wind direction.

The flow rate Q through an opening of a relatively large free area is calculated using the common orifice flow equation:

$$Q = C_d A \sqrt{(2\Delta P / \bar{\rho}} \qquad (1)$$

where C_d is the discharge coefficient of the opening, A is the opening area [m^2], ΔP is the pressure difference across the opening [Pa] and ρ is the air density [kg/m^3]. The discharge coefficient is a function of the temperature difference, wind speed and opening height (Pelletret et al, 1991). Specific expressions for the discharge coefficient are given in Allard (1998). Experiments to determine the discharge coefficients are reported by Flourentzou et al (1998).

Calculation of airflow through large openings is a complicated task. Simplified, network, zonal and computational fluid dynamic (CFD) models may be used to calculate the airflow rate in naturally ventilated buildings. A review of the commonly used models is given by Vollebregt et al (1998) and Allard (1998). Simplified models are based on experimental or simulated data and generally propose simple formulas or graphs for designing the envelopes of naturally ventilated buildings (Chandra et al, 1986; Ernest, 1991; CSTB, 1992; Etheridge, 2002; Fracastoro et al, 2002). These tools must always be used in the limits of their validity. Zonal models are based on the equations of mass and energy conservation. A zone is divided into several macroscopic homogeneous cells in which mass and heat conservation must be obeyed (Lebrun, 1970; Howarth, 1985; Inard and Buty, 1991, 1996; Togari et al, 1993; Rodriguez et al, 1994; Wurtz et al, 1996, Haghighat et al, 2001) Zonal models can quite accurately predict the temperature patterns in a room; but their main limitation is that a pre-knowledge of the flow pattern is necessary.

Network calculation models are the more commonly used tools. Network models are based on the equation of mass conservation, combined with some empirical knowledge. Well-known network models for natural ventilation systems are AIOLOS (Dascalaki and Santamouris, 1998b), COMIS (Allard et al, 1990), CONTAM (Walton 1994) and BREEZE, (BREEZE, 1993). Most of these models can be used for mechanical ventilation calculations as well.

Ventilation and thermal comfort

Energy savings associated with the use of ventilative cooling techniques are fully linked to applied thermal comfort standards. In parallel, thermal comfort is linked, as well, with the perception of indoor air quality in a building and productivity (Humphreys et al, 2002; McCartney and Humphreys, 2002). Existing standards and methods primarily cover thermal comfort conditions under steady-state conditions. The most well-known and widely accepted methods are the 'comfort equation' proposed by Fanger (1972) and the J. B. Pierce two-node model of human thermoregulation (Gagge, 1973; Gagge et al, 1986). Based on these models, several steady-state thermal comfort standards have been established (Jokl, 1987; ASHRAE, 1992; ISO, 1994).

Because of the thermal interaction between a building's envelope, its occupants and the auxiliary system, steady-state conditions, in practice, are rarely encountered in buildings. In particular, indoor temperature in free-floating buildings is far from steady. Monitoring of passive solar buildings with a constant set-point has shown that there are important indoor fluctuations of between 0.5 and 3.9 °C as a result of the control system (Madsen, 1987). Thus, knowledge of thermal comfort under transient conditions is necessary.

Field studies and basic thermal comfort research (Humphreys, 1975) have shown that there is an important discrepancy in the steady-state models, especially for the zones where no mechanical conditioning is applied. This is mainly due to the temporal and spatial variation of the physical parameters in the building (Baker, 1993). In fact, occupants living on a permanent basis in air-conditioned spaces develop expectations for low temperatures and homogeneity and are critical when indoor conditions deviate from the comfort zone that they are used to. On the contrary, people who live in naturally ventilated buildings are able to control their environment and become used to climate variability and thermal diversity. Thus, their thermal preferences extend to a wider range of temperatures or air speeds. Such an adaptation to the thermal environment has been extensively studied and documented, (Nicol et al, 1995; Brager and De Dear, 1998, 2000; De Dear, 1998; De Dear and Brager, 1998; Rijal et al, 2002).

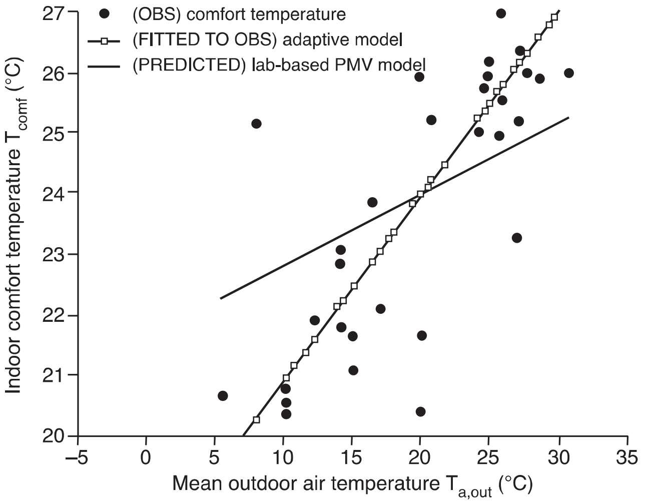
Field surveys have verified that comfort temperature is very closely related to mean indoor temperature (Nicol et al, 1999; McCartney and Nicol, 2002). Nicol and Humphreys (1973) suggested that such an effect could be the result of the feedback between the thermal sensation of subjects and their behaviour.

The adaptive principle has also been verified through the PASCOOL research project. Based on previous work, the comfort group of the European research project PASCOOL (Baker, 1993; Baker and Standeven, 1994; Standeven and Baker, 1994) has carried out field measurements to understand the mechanisms by which people make themselves comfortable at higher temperatures. It was found that people are comfortable at much higher temperatures than expected, while it was observed that people take a number of actions to make themselves comfortable, including moving to cooler parts of the room. It is characteristic that there were 273 adjustments to building controls and 62 alterations to clothing out of 864 monitored hours.

Various other research studies have verified the adaptive comfort approach. Klitsikas et al (1995) have performed comfort studies in office buildings in Athens, Greece, during the summer period. It was found that the theoretical predicted mean vote (PMV) value is almost always higher or equal to the measured thermal sensation vote, and the subjects felt more comfortable than predicted by the PMV theory. Lin Borong et al (2004) have performed comfort studies in Chinese naturally ventilated buildings. They concluded that the thermal sensation of people has a larger range than that in a stable environment. Comparisons have been performed against the PMV scale and it has been found that the PMV model, when applied to unstable or natural thermal environments to evaluate people's thermal sensation, needs correction. Similar results have been found during a comfort survey under hot and arid conditions in Israel (Becker et al, 2003), in Singapore (Hien and Tanamas, 2002), in Indonesia (Feriadi, 2002a), in Algeria (Belayat et al, 2002) and in Bangladesh,Mallick, 1994).

Humphreys and Nicol (2002) and Parsons et al (1997) have provided some explanations for the errors in the PMV theory. According to the authors, since PMV is a steady-state model there is a theoretical contradiction between the basic assumptions of the model and the imbalance assumed if the body is not comfortable. Another reason is related to the uncertainty and the fuzziness to exactly calculate the metabolic heat and clothing insulation.

Important research has been carried out in order to develop an adaptive comfort standard. Analysis of the data included in the ASHRAE RP-884 database involving data of comfort surveys around the world (De Dear and Brager, 2002) has shown that while PMV predictions fit very well with the preference of occupants in heating, ventilating and air-conditioning (HVAC) buildings, occupants of naturally ventilated buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns (see Figure 8.2).



Source: De Dear and Brager (2002)

Figure 8.2 *Observed (OBS) and predicted indoor comfort temperatures from ASHRAE RP-884 database for naturally ventilated buildings*

The same conclusions have been reported from various comfort field studies (Webb, 1959; Nicol, 1973; Humphreys, 1975; Busch, 1992; Nicol and Roaf, 1994; Matthews and Nicol, 1995; Taki et al, 1999; Nicol et al, 1999; Bouden and Ghrab, 2001) As a result of the field studies, it was proposed that optimum comfort temperature is a function of the outdoor temperature, and may be predicted by equations of the following form (Humphreys, 1978; Auliciems and De Dear 1986; Nicol and Raja, 1995):

$$T_{comf} = a\, T_{a,out} + b \tag{2}$$

where $T_{a,out}$ is the mean outdoor air temperature. Thus, De Dear and Brager (2002) have proposed the following expression:

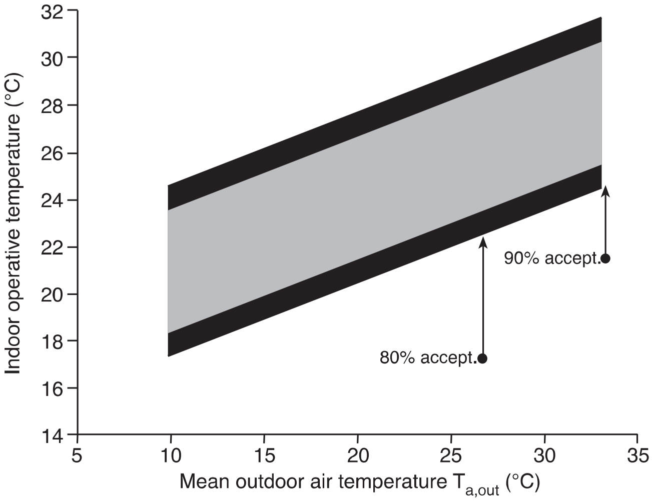
$$T_{comf} = 0.31 T_{a,out} + 17.8 \tag{3}$$

while Humphreys (1978), Humphreys and Nicol (2000) and Nicol (2002) have proposed an almost similar expression:

$$T_{comf} = 0.534 T_{a,out} + 11.9 \tag{4}$$

Based on these results, a new adaptive thermal comfort for naturally ventilated buildings has been proposed to be integrated within ASHRAE Standard 55 (see Figure 8.3).

Designing for ventilative cooling requires knowledge of the appropriate air speed inside buildings. However,



Source: De Dear and Brager (2002)

Figure 8.3 *Proposed adaptive comfort standard (ACS) for ASHRAE Standard 55, applicable for naturally ventilated buildings* the impact of air movement on thermal comfort is an open research area (Arens et al, 1984; Arens and Watanabe, 1986; Tanabe and Kimura 1994). Air velocity affects both convective and evaporative losses. Recently, studies performed in tropical climates (De Dear, 1991; Mallick 1996; Hien and Tanamas, 2002), confirm that the increase in air velocities, especially at higher temperatures, enhances thermal comfort conditions. According to Kukreja (1978), indoor air speed in warm climates should be set at 1.00–1.50m/s. Hardiman (1992) proposes an air speed of between 0.2–1.5m/s for light activity. Hien and Tanamas (2002) report that undesirable effects of high air movements of above 3m/sec have been observed.

Similar results are also reported from a recent Danish climatic chamber research project (Toffum et al, 2000), where the subjects preferred 28° C when permitted to select their own preferred airspeed than 26° C, with a fixed air speed of 0.2m/sec.

Adaptive and variable indoor temperature comfort standards for air-conditioned buildings may result in remarkable energy savings for cooling (Auliciems, 1989; Milne, 1995; Wilkins, 1995; Hensen and Centrenova, 2001). Estimated energy savings of more than 18 per cent over that from using a constant indoor temperature are reported by Stoops et al (2000), while the corresponding energy savings for UK conditions have been estimated at close to 10 per cent.

Designing for natural ventilation and cooling

Direct ventilative cooling

Natural ventilation may be used directly for cooling purposes when the ambient temperature and humidity are within comfort limits. This technique is a common practice in mild climates; but in hot areas, indirect natural ventilative cooling techniques, such as night ventilation, may be used. The exact boundaries of outdoor temperature and humidity within which indoor comfort can be provided by daytime natural ventilation have been proposed by Givoni (1994). For an indoor wind speed of 2m/sec, the upper suggested outdoor temperature for hot developed countries is close to 32° C.

The potential of direct ventilative cooling techniques has been assessed worldwide through detailed experimental and theoretical studies. The expected reduction of the cooling needs varies as a function of local climatic conditions; but a mean maximum contribution of close to 50 per cent of the needs has frequently been reported. In particular, Chandra et al (1986) have calculated the potential of direct natural ventilation techniques to reducing the cooling needs of buildings in the US. They concluded that the possible reduction of cooling needs varies between 10–50 per cent as a function of climatic characteristics. Carrol et al (1982) have simulated the impact of natural ventilation in office buildings in the US. Energy savings varied from 25 per cent in humid climates up to 50 per cent in warm climates. Vieira and Parker (1991) have found that in Florida, US, the longer the natural ventilation season can be extended, the lower overall air-conditioning consumption will be. Data from 384 single-family homes, apartments and condominiums have shown that each month, from May to September, a household claimed to use natural ventilation rather than air conditioning, resulted in an average savings of 777 kilowatt hours (kWh).

In Europe, Emmerich et al (2001) have reported that natural ventilation in the UK may provide cooling energy savings of the order of 10 per cent and fan power savings of the order of 15 per cent of annual energy consumption. Cardinale et al (2003) have studied the cooling potential of daytime natural ventilation in major Italian cities. They report energy savings of up to 53 per cent compared to an air-conditioned building. Santamouris and Fleury (1989) have studied the cooling potential of daytime ventilation in Greece and found that it is possible to cover almost 30 per cent of the cooling load of an air-conditioned building. Aynsley (1999) has also studied the possibility of providing comfort using natural ventilation for a building located in the Australian tropics. He concluded that the proper design of building permits thermal comfort to be achieved for most of the hot period.

Important tools to assess the potential of direct ventilative cooling techniques have been developed under the framework of the URBVENT research project by the European Commission. Germano et al (2002) have developed a tool to estimate the natural ventilation potential, as well as the passive cooling potential, of urban buildings. The method uses geographic information system (GIS) techniques, as well as multi-criteria evaluation, and may assist designers integrating natural ventilative cooling techniques in urban buildings. In the framework of the same research project, Ghiaus and Allard (2002) have developed a method to assess the potential of direct natural ventilative cooling using degree hours data.

Architectural integration of openings

The overall architectural design of a building determines its ventilation and passive cooling potential. Vernacular architecture in warm climates is full of ideas and examples on how to better integrate natural ventilation and passive cooling in buildings (Fathy, 1986).

Techniques to enhance natural ventilation in buildings have been well researched, and appropriate strategies involving reduction of the plan depth, maximization of the skin permeability through openings, minimization of internal obstructions, increased openness, orientation to prevailing winds, and use of the stack effect are among the main proposed strategies (Fleury, 1990; Hyde, 2000). The CIBSE *Applications Manual* (CIBSE, 1997) and Martin (1995) describe several natural ventilation configurations incorporating advanced windows, window and vent actuators, thermal chimneys, wind chimneys, atria, etc.

The overall architecture of a building and, in particular, the positioning and shape of the openings, balconies and internal partitions, as well as the shape of the building, play a very important role and determine the air speed and comfort conditions in naturally ventilated buildings. Important research has been carried out in trying to optimize the main architectural parameters (Olgay, 1973; Sobin, 1981; Kindangen et al, 1996, 1997; Chand et al, 1998; Chiang et al, 2000; Prianto et al, 2000; Prianto and Depecker, 2002). Givoni's (1976) pioneering work on the position of openings in naturally ventilated buildings has permitted a better understanding of the specific contribution of windows to different boundary conditions.

Rosenbaum (1999) has summarized some of the main conclusions of research on the position of walls and proposed techniques to enhance airflow through the building's envelope. The main suggestions are:

- In order to enhance cross-ventilation, irregularly shaped or spread-out buildings have to be designed.
- It is better to face the building at an oblique angle to the prevailing wind than to face it directly perpendicular to the wind direction.
- The inlet area should be equal to the outlet area.
- Horizontally shaped windows perform better than vertical windows.

Other building elements may be used to enhance airflow in naturally ventilated buildings. In particular, verandas, balconies and decks may contribute to significantly increasing the air speed inside a building because pressure differences may also increase (Chand, 1973a). As reported, when the angle of incidence ranges from 0–60 degrees, the windward or leeward location of a veranda open on three sides produces an important air motion in a room. In parallel, the use of pelmet-type wind deflectors enhance the air movement at a working plane in a room by about 30 per cent (Chand et al, 1975). In addition, sashes projecting outward result in enhanced indoor air motion compared with those projected inward (Chand and Bhargava, 1975).

Single-sided naturally ventilated buildings may not present a high airflow rate because of the specific pressure difference. Givoni (1976) has proposed the use of wing walls in windward openings that permit the creation of distinct positive and negative pressures on the openings and, thus, enhance the airflow in the building. Givoni (1976) reported that for oblique winds, the use of wing walls created an average air velocity in the room of about 40 per cent of the outside wind, while when no wing walls were used, the air speed was just 15 per cent of the ambient wind.

Chandra et al (1983), have carried out full-scale experiments to measure the performance of wing walls. Airflow was measured in a room with and without wing walls. They found that the presence of the wing walls considerably increases the inlet air speed to the room.

Atria and courtyards

Ventilated atria and courtyards attached to buildings may enhance natural ventilation and promote convective cooling. Courtyards are well known from ancient times. They were used in ancient Greek and Roman architecture, as well as in Mesopotamia, the Indus Valley, the Nile Valley and in China. Their overall form and construction have endured over 6000 years with very few modifications, (Hinrichs, 1988).

Courtyards are associated with naturally ventilated buildings in hot climates. Atria and courtyards are generally hotter during the daytime but present a much lower temperature during the night (Chandra, 1989). Courtyards are transitional zones that improve comfort conditions by modifying the microclimate around the building and by enhancing the airflow in the building. Important research has been carried out to better understand the airflow processes and the cooling impact of courtyards (Bagneid, 1987; Etzion, 1988; Hoffman et al, 1994; Berger and Semega, 1995; Cadima, 2000; Majid et al, 2002; Feriadi, 2002b). A classification system of atria as well as an extensive literature review has been prepared by Eureca Laboratories (1982).

In a recent paper, Rajapaksha et al (2003) have studied the potential of a ventilated courtyard to provide passive cooling in buildings located in warm, humid climates. It was found that the overall performance depends upon the flow patterns. Better performance is reported when the courtyard acts as an air funnel, discharging indoor air into the sky.

Methods and tools to design atria and estimate the airflow through them have been proposed by Hunt and Holford (1998), Holford and Hunt (2000), Gage et al

(2001), Todorovic et al (2002) and Holford and Hunt (2003).

Solar chimneys

Solar chimneys have been extensively studied as a configuration to implement natural ventilation in buildings where solar energy is available. Solar chimneys are natural draught components that utilize solar energy to build up stack pressure and, thus, drive airflow through the chimney channel. Solar chimneys are similar to conventional chimneys except that the south wall is replaced by a glazed surface, which enables it to collect solar radiation (Haisley, 1981; Kumar et al, 1998; Afonso and Oliveira, 2000). Such a technique, called 'Scirocco room', is well known from traditional Italian architecture of the 16th century (Cristofalo et al, 1989). Quite recently, important experimental, numerical and theoretical research has contributed to a better understanding of solar chimneys.

The ability of solar chimneys to improve the ventilation rate in naturally ventilated buildings was studied by Bansal et al (1993, 1994). It was found that the impact of solar chimneys is substantial in inducing natural ventilation for low wind speeds. Gan and Riffat (1998) and Shao et al (1998) have also studied a solar-assisted technique to enhance natural ventilation, coupled with a heat-pipe heat-recovery system. They report a heat recovery efficiency of about 50 per cent. The performance of solar chimneys when integrated with air-conditioned buildings has been studied by Khedari et al (2003). It was reported that the solar chimney could reduce the average electrical consumption of the building by 10–20 per cent. The contribution of solar chimneys to improving ventilation and cooling in hot climates was studied by Bouchair, (1987, 1989, 1994) and Tan (2000). Theoretical models and simulation techniques to calculate the performance of solar chimneys have been proposed by Pedki and Sherif (1999), Rodrigues et al (2000) and Letan et al (2003).

Passive and active stacks have been incorporated within a high-rise residential building in Singapore (Priyadarsini et al, 2003). It was found that passive stacks cannot change the air velocity in the building, while the use of active stacks leads to a substantial increase in air velocity within the rooms. Similar results on the use of active stacks in naturally ventilated buildings are reported by Hien and Sani (2002).

Solar chimneys with a uniform heat flux on a single wall were investigated experimentally for different chimney gaps, heat flux inputs and different chimney inclinations by Chen et al (2003). No optimum gap was found, while it was reported that the airflow rate reached a maximum at a chimney inclination angle of around 45 degrees. This is about 45 per cent higher than that for a vertical chimney under otherwise identical conditions.

The integration of solar chimneys with cooling cavities to enhance both ventilation and cooling has been studied by various researchers (Barozzi et al, 1992; Aboulnaga and Abdrabboh, 1998, 2000; Hamdy and Fikry, 1998; Pasumarthi and Sherif, 1998; Hunt and Linden, 1999; Khedari et al, 2000a, 2000b; Li, 2000; Raman et al, 2001; Day et al, 2003). Cooling cavities induce downward buoyancy airflow in a vertical cavity, where the air is cooled using mainly evaporative cooling techniques. It has been found that such a combination leads to increased airflow rates and an important reduction of indoor temperature depending upon the characteristics of the system.

The ventilation performance of light/vent pipes has been studied by Oliveira et al (2001). Light/vent pipes are composed of two concentric tubes. The channel space between the tubes is allowed for airflow. Air is flowing either because of the temperature difference or because of the wind pressure. Experiments have shown that light/vent components enhance the airflow by 44 per cent.

Wind towers

Wind towers or cooling towers are well known and have traditionally been used in Middle Eastern and Persian architecture (Bahadori, 1978, 1985). Air enters the towers at the windward face, its higher part, and leaves at the lower part, which is in communication with the building. The air may be cooled by evaporative or convective cooling through the tower. Research has shown that inlet and outlet opening areas for wind towers have to be 3–5 per cent of the floor area that they serve (Nielsen, 2002).

New active developments, particularly coolers where the air was forced by a fan through wetted pads, have been used during the past in desert areas of the US. In natural downdraught coolers, the air is not forced through the pads and air is provided simply by gravity flow (Cunningham and Thompson, 1986). The performance of natural downdraught coolers is studied by Badran (2003), while the necessary pressure coefficients to evaluate the airflow in wind towers are provided by Karakatsanis et al (1986) and Bahadori (1981). In parallel, the performance of downdraught evaporative coolers has been studied in detail by various authors and design tools have been proposed (Givoni, 1991; Sodha et al, 1991; Chalfoun, 1992; Thompson et al, 1994).

A high-efficiency and innovative development of the downdraught evaporative cooler is achieved through the PDEC (Passive Downdraft Evaporative Cooling) research programme of the European Commission, (PDEC, 1995). The improvement consists of replacing the wetted pads with rows of atomizers – nozzles that produce an artificial fog by injecting water at high-pressure through minute orifices. This feature produces much better regulation of the system, a significant reduction of the pressure losses and a lower size of equipment.

Innovative components

Various innovative ventilation components have been proposed for integration within buildings. Fairey and Bettencourt (1981) have proposed a roof-top ventilation component known as '*La Sucka*' that is based on the use of dampers on two or four sides of a roof-top cupola. The component permits the airflow through the leeward part of the cupola by closing the dampers in the windward façade. Fuller (1973) has proposed a 'dymaxion dwelling machine' that is a rotating roof which aligns to the wind direction, while Givoni (1968) has proposed a double-ceiling system for cross-ventilation.

Control of naturally ventilated buildings

In naturally ventilated buildings, controls have to be used to modify the indoor environment. Control can be automatic or manual by the building's occupants. Appropriate control, like window opening or use of blinds, may reduce the need for mechanical cooling. The importance of control has been clearly shown by various studies and research (Baker and Stadeven, 1995; Leaman and Bordass, 1995; Nicol et al, 1999).

Liem and van Paaseen (1998) have found that by controlling a naturally ventilated building, an improvement in the established comfort is observed; but the exact type of simple control algorithm has a marginal influence on the improvement. Kolokotroni et al (2001) have studied the performance of a naturally ventilated educational building in the UK and have concluded that although thermal mass and natural ventilation can reduce the effect of external hot weather and establish comfort in the building, manual or automatic control should be set in place so that the benefits are not offset by overcooling the building during cold spells.

Experimental surveys trying to identify the control actions undertaken by individuals in naturally ventilated buildings (Raja et al, 1998, 2001) have shown that controls are used in response to discomfort and, in general, occupants who have greater access to controls (for example, those close to a window) report less discomfort than those who have less access.

Various automatic control strategies can be used to achieve comfort in naturally ventilated buildings. Pitts and Abro (1991) have developed an intelligent controller to optimize night ventilation in a building through an active solar chimney. The controller could calculate the cooling needs, the comfort conditions in the building and the cooling capacity of the solar chimney. Thus, appropriate decisions can be taken. La Roche and Milne (2001, 2002, 2003) have designed and tested an intelligent controller to optimize the use of mechanical ventilative cooling using a whole-house fan. The controller is based on a set of decision rules that takes into account indoor and outdoor temperatures, and experimental testing has shown that this can improve indoor comfort and reduce energy consumption.

In particular, artificial intelligence techniques seem to offer numerous advantages compared to classical control systems. Such a controller, for naturally ventilated buildings, was proposed by Dounis et al (1995a, 1995b). A comparison of ON-OFF, PID and PI with deadband and fuzzy controllers for naturally ventilated buildings has been performed by Dounis et al (1996a, 1996b), and it has been shown that fuzzy controllers present important advantages compared to other conventional strategies. Eftekhari and Marjanovic (2003) have proposed a fuzzy logic controller to optimize the opening position in naturally ventilated buildings. It was found that such a controller is capable of providing better thermal comfort inside the room than a manual control of openings or seasonal operation. Kolokotsa (2001) has designed and tested a prototype fuzzy controller for naturally ventilated buildings using local operating networks and smart cards technology. The research has been carried out in the frame of the European research project BUILTECH, and has resulted in the design of a prototype controller that significantly improves indoor environmental quality in naturally ventilated buildings. Kolokotsa (2003) has also tested five different fuzzy controllers for naturally ventilated buildings, particularly fuzzy P, fuzzy PID, fuzzy PI, fuzzy PD and adaptive fuzzy PD, and has concluded that all controllers achieve important energy and comfort improvements.

Indirect ventilative cooling techniques

Principles of night ventilative cooling

Night-time ventilation is associated with the circulation of low-temperature ambient air in a building and the reduction of the temperature of indoor air, but mainly of storage mass. Thus, indoor thermal conditions in a building are more positive during the following day. Night-time ventilation is suitable for areas with a high diurnal temperature range and where night-time temperature is not so cold as to create discomfort.

Night ventilation systems are classified as direct or indirect, depending upon the procedure used to transfer heat between the thermal storage mass and the conditioned space. In direct systems, cool air is circulated inside the building zones and heat is stored in the exposed opaque elements of the building. The reduced temperature mass of the building contributes to reducing the indoor temperature of the following day through convective and radiative procedures. Circulation of the air can be achieved by natural or mechanical ventilation. In direct systems, the mass of the building has to be exposed and the use of coverings or false floors or ceilings has to be avoided (Santamouris, 2003).

In indirect systems, cool air is circulated during the night through a thermal storage medium where heat is stored and is recovered during the following day period. In general, the storage medium is a slab covered by a false ceiling, a floor or a phase-change material storage, while the circulation of the air is always forced. It is evident that during the day period, the temperature of the circulated air has to be higher than the corresponding temperature of the storage medium. Direct and indirect night ventilation systems are used many times in a combined way.

Thus, night ventilation affects indoor conditions during the next day in four ways by: (Kolokotroni and Aronis, 1999):

1. reducing peak air temperatures;
2. reducing air temperatures throughout the day and, in particular, during the morning hours;
3. reducing slab temperatures; and
4. creating a time lag between the occurrence of external and internal maximum temperatures.

It is evident that the performance of night cooling systems depends upon three main parameters:

1. the temperature and the flux of the ambient air circulated in the building during the night period;
2. the quality of the heat transfer between the circulated air and the thermal mass;
3. the thermal capacity of the storage medium.

Important theoretical and experimental research has been carried out to better understand the phenomena, to evaluate the cooling potential of night ventilation techniques, and to develop computational and design tools and codes.

Extended experimental work on night ventilation techniques are reported by Baer, (1983, 1984); Agas et al (1991); Van der Maas and Roulet (1991); Geurra et al (1992); Barnard (1994); Givoni (1994, 1998a); Hassid (1994); Van der Maas et al (1994); Blondeau et al (1995a, 2002); Ren (1995); Kolokotroni et al (1996a, 1997); Meierhans (1996); Santamouris and Assimakopoulos (1996); Santamouris et al (1996); Behne (1996); Feustel and Stetiu (1997); Aboulnaga and Abdrabboh (1998); Burton (1998); Dascalaki and Santamouris (1998a); Demeester et al (1998); Geros et al (1999); Nicol et al (1998); Wouters et al (1998); Zimmerman and Anderson (1998); Roucoult et al (1999); CEC (2000b); Liddament (2000); Shaviv et al (2000); Turpenny et al (2000a); Barnard et al (2001); Blake (2001); Axley and Emmerich (2002); Herkel et al (2002) and Todorovic et al (2002).

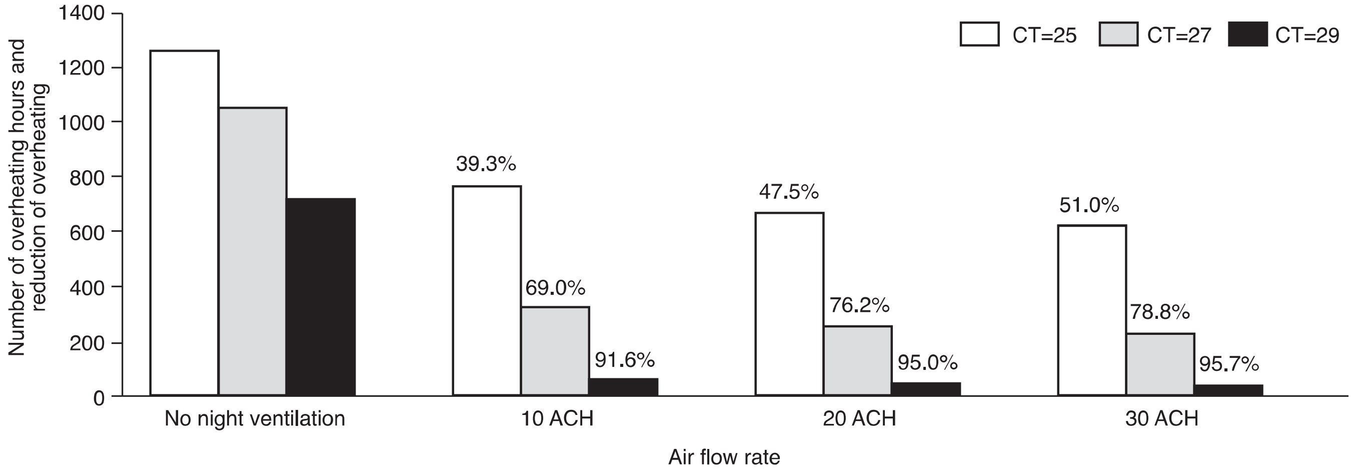
Cooling potential of night ventilative techniques applied to free-floating buildings

Various important theoretical and experimental works have been performed in order to assess the efficiency of night-cooling techniques applied to free-floating buildings. Most of the research shows that it is possible to reduce the peak indoor temperature of the next day between 0.5–3° C as a function of the airflow rate, the thermal storage capacity of the building and the daytime and night-time temperature of the ambient air.

Research carried out in southern climates has shown that the reduction of the indoor temperature during the following day may be between 2–3° C. Geros et al (1999) performed measurements in free-floating office buildings in Athens, Greece. The authors reported that under free-floating conditions, the use of night ventilation decreases the next-day peak indoor temperature by up to 3° C. Results of sensitivity analysis have shown that the expected reduction of the overheating hours varies between 39 per cent and 96 per cent for airflow rates for 10 and 30 air changes per hour (ACH), respectively (see Figure 8.4).

Shaviv et al (2001) have studied the cooling potential of night ventilation techniques in Israel for different levels of thermal mass. They showed that it is possible to achieve a reduction of 3–6° C in a heavy constructed building without operating an air-conditioning unit. Similar results are reported by Becker and Paciuk (2002) regarding the application of night ventilation techniques in office buildings in Israel.

Solaini et al (1998) have studied the performance of night ventilation techniques in an experimental building in Italy and found that these techniques play a very important role in its cooling needs. Silvestrini and Alessandro (1988) report that for Italian conditions, 3 ACH during the night may provide a good perception of comfort; when 10–15 ACH are applied, the building presents its minimum energy consumption for cooling.



Note: The building is considered to operate under free-floating conditions. CT = constant temperature.

Source: Geros et al (1999)

Figure 8.4 *Average overheating hours and reduction due to the use of night ventilation in the Meletitiki Building, Athens, Greece*

In California, Givoni (1998) measured the potential of night ventilation to reduce maximum daytime temperatures in buildings with different mass levels. It was found that night ventilation has almost no effect on the low mass building, but has an important effect in heavy buildings. When the outdoor temperature was 38° C, the indoor maximum temperature of the high mass building was only 24.5° C.

Rainaweera and Hestnes (1994) have calculated the impact of night ventilation techniques when applied in typical dwellings in Sri Lanka. They found that an increase of the flow rate from 8 ACH to 14 ACH decreases the maximum indoor temperature of the next day by 0.5° C.

Golneshan and Yaghoubi (1985, 1990) have simulated the contribution of night ventilation techniques in Iranian residential buildings. They report that the use of 12 ACH per hour during the night with 1 ACH during the day may provide comfortable indoor conditions.

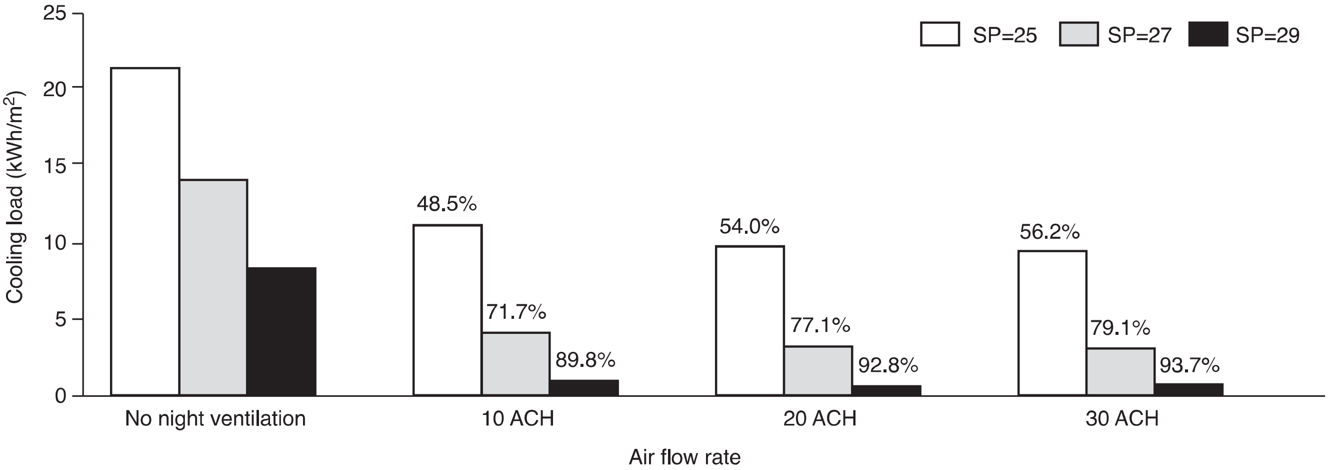
When applied in mild climates, night ventilation may reduce indoor temperatures by up to 1–2° C; but this may be sufficient to cover a very high part of comfort needs. Birtles et al (1996), as well as Kolokotroni et al (1998), have performed simulations to study the potential of night ventilation and thermal mass to cover the cooling needs of office buildings in the UK. They concluded that these techniques can provide the required cooling in most cases, while for the rest, a high percentage of the cooling requirements can be met by night ventilation.

Blondeau et al (1995b) have measured the potential of night ventilated offices in France and found that it is possible to reduce the maximum next-day indoor temperature by 1.5–2° C.

Neeper and McFarland (1982) and Kammerud et al (1984) have simulated the impact of night-ventilated massive passive solar houses in the US. They concluded that increasing the airflow by up to 10 ACH does not contribute to additional energy savings. Further studies by Chandra and Kesticioglu (1984) for the same building, considering a variable heat transfer coefficient, have shown that under specific conditions the optimum ACH is close to 25. Parker (1992) has measured the efficiency of whole-house fans to provide night cooling in a free-floating house in Florida. They report reductions of the total daily average interior temperature by over 2.5° F due to the removal of heat from the thermal mass of the building.

Cooling potential of night ventilative techniques applied to air-conditioned buildings

Night ventilation applied to air-conditioned buildings may reduce the required energy for cooling, as well as the peak electricity demand. Experiments, theoretical studies and real applications have shown that there is a very high savings potential that may exceed 50 per cent of the cooling load of massive buildings for an indoor temperature of close to 26° C and a high airflow rate. In parallel, the reduction of the peak electricity demand may decrease by up to 40 per cent. Different results are reported as a function of the climate and building characteristics, as well as of the airflow and operational conditions.



Note: The building is considered to operate under air-conditioning conditions. SP = set point.

Source: Geros et al (1999)

Figure 8.5 *Cooling load reduction due to the use of night ventilation in the Meletitiki Building, Athens, Greece*

Geros et al (1999) performed measurements in air-conditioned night-ventilated office buildings in Athens, Greece. They found that the early morning indoor air temperature can be reduced by 0.8–2.5° C depending upon the considered set-point temperature. Sensitivity analysis that attempts to identify the impact of airflow rates, as well as of the set-point temperature, has shown that the expected energy conservation varies between 48 per cent and 94 per cent for set-point temperatures of between 26–29° C and airflow rates of between 10 and 30 ACH, respectively (see Figure 8.5).

A similar analysis has been performed by Blondeau et al (1995), who have studied the cooling potential of night ventilation techniques when applied to an air-conditioned building in France. It is found that the lower the set-point temperature during daytime, the lower the contribution of night cooling. For a 22° C temperature set-point, night ventilation covers almost 12 per cent of the cooling load, while when the set-point temperature rises to 26° C, the corresponding contribution increases to 50 per cent of the load.

Carrilho da Graca et al (2002) have simulated the effect of night ventilation in a six-storey apartment in Beijing and Shanghai. They found that night cooling may replace air conditioning for about 90 per cent of the time in Beijing and 66 per cent in Shanghai. Olsen and Chen (2003) have studied the performance of night ventilation techniques coupled with a variable air volume flow rate (VAV) and a displacement ventilation system for an office building in the UK. They found that when night ventilation is associated with a VAV system, it contributes to reducing the energy consumption for cooling by 12 per cent. In parallel, the peak chiller load is reduced by about 20 per cent for both the displacement ventilation and VAV systems when night cooling is used.

Kolokotroni and Aronis (1999) have studied the impact of night ventilation techniques in air-conditioned offices in the UK. They reported that application of night ventilation is beneficial and results in an energy saving of about 5 per cent and an installed capacity saving of about 6 per cent, while for heavyweight buildings the figures increase to about 15 and 12 per cent, respectively.

Martin et al (1984) have simulated the impact of night ventilation in air-conditioned non-residential buildings in Los Angeles, Atlanta and New York. They found that in Los Angeles, cooling energy consumption can be reduced by up to 7 per cent by night ventilation with 3 ACH. Increasing the airflow to 30 ACH does not contribute to additional benefits. In Atlanta, night ventilation has no impact in low-mass buildings, but it contributes to reducing the cooling load of high-mass buildings by 6–7 per cent for 3 ACH during the night. The performance is not improved significantly when 30 ACH are applied. Finally, in New York, small benefits can be achieved in high-mass buildings.

Various studies have considered the use of whole-house fans to provide night ventilation. Studies by Kusuda (1981) in air-conditioned buildings have shown that the use of whole-house fans to provide night-time ventilation may contribute to reducing the air-conditioning load by up to 56 per cent. Similar studies are reported by Burch and Treando (1979) and Ingley et al (1983). Burch and

Table 8.4 *Reduced electrical peak power demand of a building for different night ventilation strategies (percentage)*

		Berlin, Germany	Locarno, Switzerland	Red Bluff, US	San Francisco, US
No chiller	Natural night ventilation	-40^2	-52^1	–	–31
	Mechanical night ventilation	-38^2	-51^1	–	–29
With chiller	Mechanical night ventilation	–30	–28	0	–9

Notes: 1 Room temperatures and humidity levels are frequently beyond the thermal comfort range.

2 Indoor air humidity might exceed 60 per cent relative humidity (RH) for about 200h/a (hours per annum).

Source: Behne (1996)

Treando (1979) measured the performance of whole-house fans installed in an air-conditioned house in Houston, Texas, that was used to provide night ventilation. They found that on days when the daily average temperature was below 75° F, the whole-house fan was able to satisfy all of the cooling requirements. Savings in air-conditioning consumption from use of the whole-house fan varied between 6.5–10 per cent. Ingley et al (1983) performed a similar experiment in Florida and reported a 22 per cent electricity saving for the house with the whole-house fan while the daily air-conditioning use was reduced by 44 per cent on milder summer days.

Behne (1996) has performed a detailed study to evaluate the potential of night ventilated buildings under various operational conditions. The study has been performed for Berlin, Germany; Locarno, Switzerland; Red Bluff, US; and San Francisco, US. Naturally and mechanically ventilated free-floating and mechanically ventilated air-conditioned buildings have been considered. As shown in Table 8.4, under natural ventilation conditions, peak power gains vary between 31 per cent for San Francisco and 52 per cent for Locarno, while the peak power conservation in air-conditioned buildings varies from 9 per cent for San Francisco to 30 per cent for Berlin.

Slab cooling

In indirect systems, cool night air is circulated through a thermal storage medium where heat is stored and recovered during the day period. In general, the storage medium is a slab covered by a false ceiling or floor, while circulation of the air is always forced. During the following day, the temperature of the circulated air has to be higher than the corresponding temperature of the storage medium. A design analysis of this concept for office buildings is given by Barnaby et al (1980). Slab cooling combined with phase change materials (PCM) storage has been applied in a real building in the UK by Barnard (1994; Barnard et al, 2001).

Fleury (1984) simulated the impact of night cooling through hollow-core concrete floor slabs in a small office building in Los Angeles and New York. No important benefits have been found for New York, while in Los Angeles, when a suitable control strategy was followed, the total energy consumption was reduced by 13 per cent and the total electricity peak demand was reduced by 7 per cent.

Use of phase change materials (PCM)

Phase change materials can be used to store energy during the night and to recover it during the day. Cool air is circulated during the night at the PCM store and is stored under the form of latent heat. During the following day, the high-temperature ambient air is circulated through the PCM, where the latent heat offered to the material cools the air. The efficiency of the system deals primarily with the phase change temperature of the material, the temperature of the ambient air during the night period and the airflow rate. Phase change materials can be paraffin, eutectic salts, etc., and can be embedded in microcapsules, thin heat exchangers, plaster, gypsum board or other wall-covering materials.

During recent years, many research studies and experimental applications have been carried out. Kang Yanbing et al (2003) studied the use of an external PCM store associated with night ventilation techniques. A fatty acid was used as a phase change material. They found that the use of a PCM store decreases the maximum room temperature of the next day by almost 2° C, compared to a commonly night-ventilated building.

Turpenny et al (2000a, c) have proposed and tested a PCM storage with embedded heat pipes, coupled with night ventilation. A high heat-transfer rate was measured and it was concluded that the system can ameliorate the performance of night cooling techniques.

The use of PCM wallboard coupled with mechanical night ventilation in office buildings has been studied by Stetiu and Feustel (1996). They concluded that PCM storage associated with night ventilation techniques offers the opportunity for system downsizing in climates where the outside air temperature drops below 18° C at night. Calculations for a prototype IEA (International Energy Agency) building located in California show that PCM wallboard could reduce the peak cooling load by 28 per cent.

Modelling night ventilation

Proper design of buildings using night-ventilation cooling techniques needs to consider all of the parameters that define the energy and environmental performance of buildings. The use of detailed simulation programmes using well-validated algorithms is the more appropriate method to achieve the best possible efficiency and global performance.

When detailed simulation codes are not used, more simplified assessment methods may be employed. During recent years, several codes have been prepared to calculate the specific performance of night ventilation techniques. These tools are designed to help architects and engineers to consider in a more simplified but accurate way the sizing of night cooling techniques. In what follows, information on some of the data is provided.

NiteCool (Tindale et al, 1995) was developed especially for assessing a range of night-cooling ventilation strategies and was designed under the Energy Related Environmental Issues in Buildings (EnREI) Department of the Environment (DOE) programme in the US. The tool is based on single zone ventilation. LESOCOOL is another simple computer tool to evaluate the potential of night ventilative cooling (Roulet et al, 1996). LESOCOOL calculates the cooling potential and the overheating risk in a naturally or mechanically ventilated building, showing the temperature evolution, the airflow rate and the ventilation heat transfer. It can also take into account convective or radiative heat gains.

Santamouris et al (1996) have proposed a detailed methodology to calculate the performance of air-conditioned as well as free-floating night-ventilated buildings. The method is based on the principle of modified cooling degree days and is extensively compared against theoretical and experimental data. The method is integrated within the simulation tool SUMMER (Santamouris et al, 1995) and calculates the variation of the balance point temperature of a free-floating or air-conditioned night-ventilated building, as well as the overheating hours and the cooling load. In parallel, it performs comparisons with a conventional free-floating or air-conditioned building.

Givoni (1992, 1998a), has proposed a formula to predict the expected indoor maximum temperature with different amounts of mass and insulation in a night ventilated building. Shaviv et al (2001) has proposed a method to estimate the decrease of the maximum temperature from the diurnal temperature swing as a function of the amount of thermal mass and the night ventilation rate.

(Millet, 1997) has proposed a simplified resistance capacitance model that takes into account the thermal inertia of the building and the impact of night ventilation. Attention is paid to the impact of the outdoor noise (related to the windows opening at night). This model was validated by comparing its results to a more detailed one (TRNSYS) and was used to produce guidance rules.

Finally, Stein and Reynolds (1992) have proposed calculation methods and rules of thumb to estimate the amount of heat that can be removed from the building for given boundary conditions in a night ventilated building.

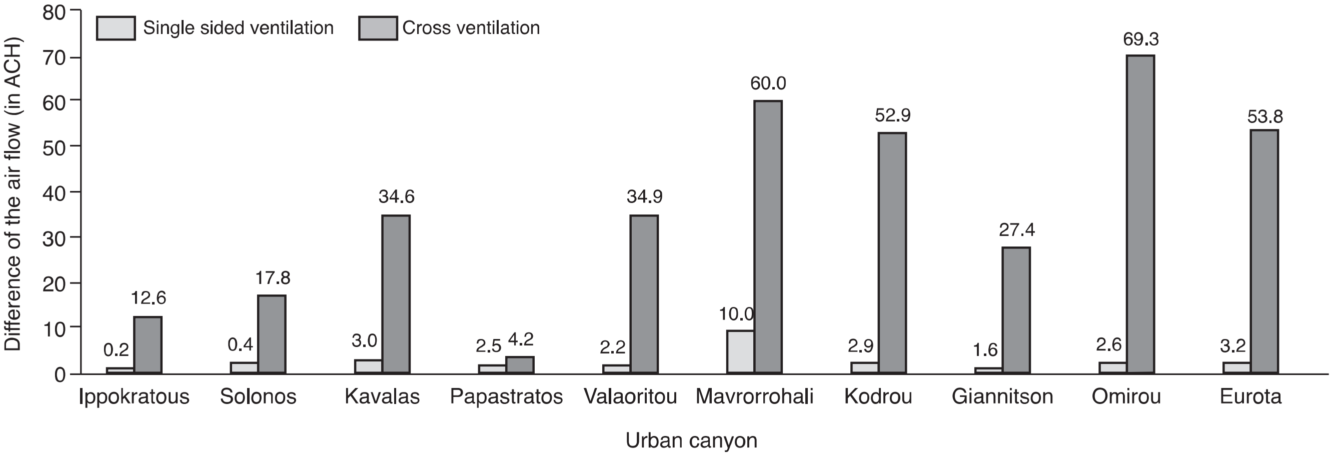
Constraints and limitations of ventilative cooling techniques

Ventilative cooling is a very powerful technique, but it presents important limitations. Main problems are associated with noise and pollution, reduction of the wind speed in the urban environment and moisture control. In fact, moisture and condensation control is necessary, particularly in humid areas. Pollution and acoustic problems, as well as problems of privacy, are associated with the use of natural ventilation techniques.

Outdoor pollution presents a serious limitation for naturally ventilated buildings, especially in urban areas. Stanners and Bourdeau (1995) have estimated that in 70 to 80 per cent of European cities with more than 500,000 inhabitants, the levels of air pollution, regarding one or more pollutants, exceeds the World Health Organization (WHO) standards at least once per year. Air cleaning through filtration can be applied when mechanical ventilation or flow-controlled natural-ventilation components are used. Noise can be a serious limitation for naturally ventilated buildings. Stanners and Bourdeau (1996) reported that unacceptable noise levels of more than 65dBA affect between 10–20 per cent of urban inhabitants in most European cities. In parallel, as estimated by the Organisation for Economic Co-operation and Development (OECD) (OECD, 1991), almost 130 million people in OECD countries are exposed to noise levels that are unacceptable.

Recent research has shown that the most significant limitation of natural ventilation techniques is due to the specific climatic conditions of cities. Because of specific urban characteristics, there is a serious increase in ambient temperature because of the heat island effect, as well as a serious decrease in wind speed in urban canyons. Both reasons seriously decrease the cooling potential of natural and night-ventilative cooling techniques.

Geros et al (2001) have carried out specific experiments in ten urban canyons in Athens to study the reduction of the airflow in single-sided and naturally



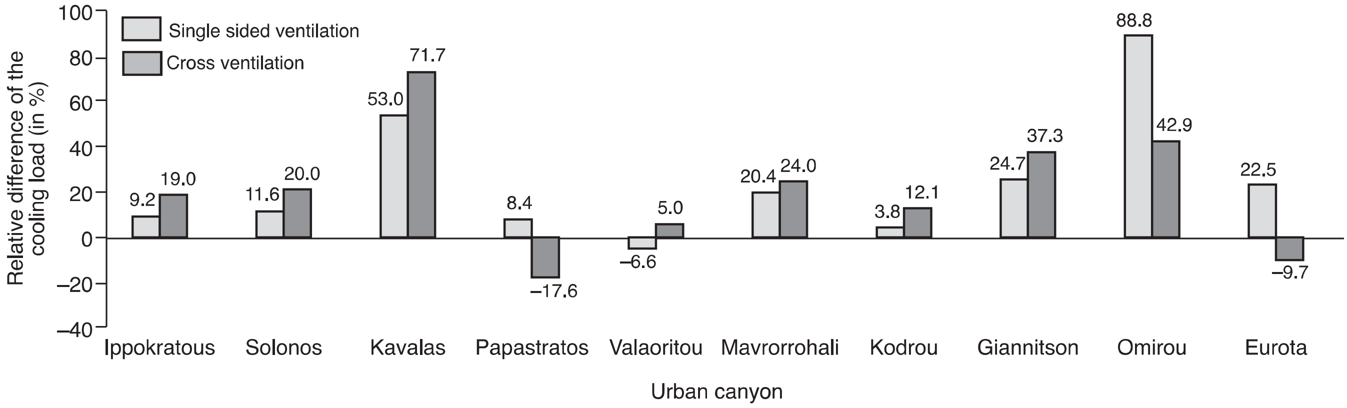
Source: Geros et al (2001)

Figure 8.6 *Reduction of air change rate for single-sided and cross-ventilated buildings in ten urban canyons*

cross-ventilated buildings. They found that because of the reduced wind speed, the airflow through the buildings can decrease by up to 90 per cent (see Figure 8.6). Thus, efficient integration of natural and night ventilation techniques in dense urban areas requires full knowledge of wind characteristics, as well as adaptation of ventilation components to local conditions.

Geros et al (1999) have compared the cooling load of a night ventilated building when located in ten specific urban canyons against the load of the same building located in a non-obstructed site. They reported that because of the reduced wind speed in the canyons, the cooling load of urban buildings increases by between 6–89 per cent for the single-sided ventilation, and by between 18–72 per cent for the cross-ventilated building depending upon the characteristics of the canyon (see Figure 8.7)

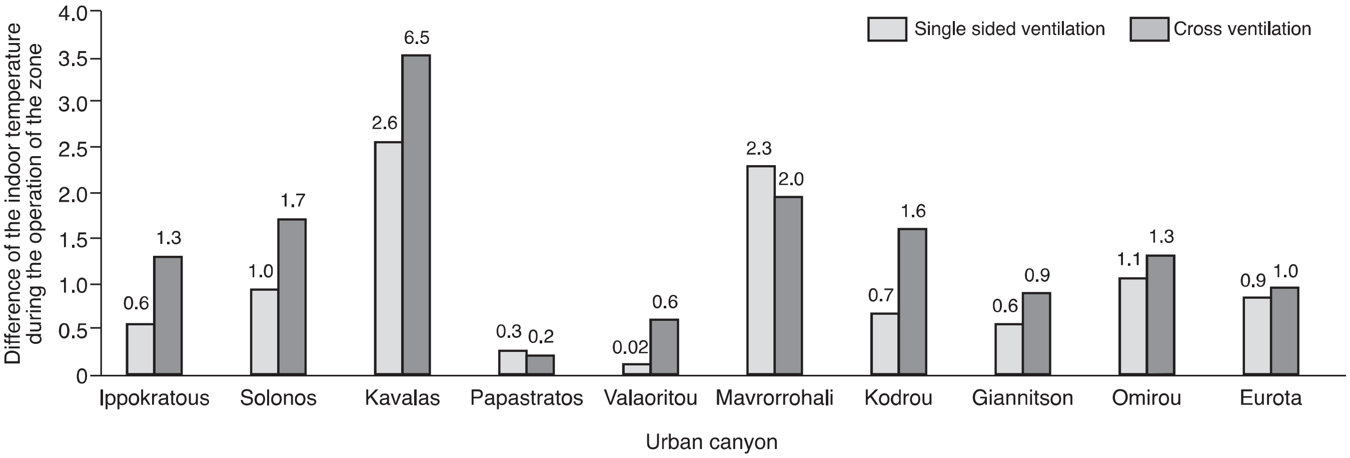
In parallel, a similar comparison has been performed for a free-floating night-ventilated building (Geros et al, 1999). It has been calculated that the maximum indoor temperatures of the urban buildings increase between 0.0–2.6° C for single-sided buildings and between 0.2–3.5° C for cross-ventilated buildings, depending upon the characteristics of the canyon. Figure 8.8 illustrates the specific differences for the ten urban canyons. Thus, a



Note: The analysis refers to ten urban canyons where experiments have been performed and results are given for the single-sided and cross-ventilated buildings.

Source: Geros et al (1999)

Figure 8.7 *The difference of the cooling load calculated for a night ventilated building located in a canyon and in a non-obstructed site*



Note: The analysis refers to ten urban canyons where experiments have been performed and results are given for the single-sided and cross-ventilated buildings.

Source: Geros et al (1999)

Figure 8.8 *The difference between the maximum indoor air temperature calculated for a night ventilated building located in a canyon and in a non-obstructed site*

correct sizing and design of night-cooled buildings using natural ventilation techniques has to be based on data appropriate for urban locations.

Use of fans and mechanical ventilation systems to provide thermal comfort

Use of fans for comfort

Box fans, oscillating or ceiling fans can increase the interior air speed and improve comfort (Chand, 1973b; Chandra, 1985). Higher air speeds permit the building to be operated at a higher set-point temperature and thus to reduce its cooling needs. As reported by Chandra et al (1986), for every degree Fahrenheit increase of the thermostat during the summer, the cooling load is decreased by 7–10 per cent. Air-circulation fans allow the thermostat to increase by 4° F; thus, fans can contribute up to 40 per cent of the cooling needs of buildings under the assumption that the occupants are always close to the fan. James et al (1996) have shown that the additional use of ceiling fans in air-conditioned buildings contributes to substantial savings of energy if the air-conditioning set-point is lowered.

Ceiling fans have dominated the US market. According to a study by Ecos Consulting and the Natural Resources Defense Council of the USA (2001), two out of every three homes in the US have at least one ceiling fan, and, on average, each fan consumes about 130kWh per year. In total, there are almost 193 million ceiling fans in the US. Ceiling fans can save energy when users raise air-conditioning thermostats. Rohles et al (1983) and Scheatzle et al (1989), have shown that ceiling fans can extend the comfort zone outside the typical ASHRAE comfort zone. In particular, at an air velocity of 1.02m/sec, comfort may be achieved at 27.7° C for 73 per cent relative humidity, 29.6° C for 50 per cent humidity and 31° C for 39 per cent relative humidity. Fairey et al (1986) have shown that the use of ceiling or oscillating fans may significantly contribute to reducing the cooling load of buildings in the southern US if the thermostat settings are raised accordingly. As reported, energy savings of about 30 per cent are calculated for typical frame buildings in Orlando and Atlanta by increasing the thermostat setting from 25.56° C to 27.78° C. The energy savings may increase by up 50 per cent for heavy-mass buildings.

In the Florida climate, savings are roughly 14 per cent for a 2° F increase, according to the Florida Solar Energy Center. Although studies suggest a 2–6° F increase in the thermostat set-point, James et al (1996) report that in 386 surveyed Florida households, they have not identified any statistically valid differences in thermostat settings between houses using fans and those without them, although fans were used an average of 13.4 hours per day.

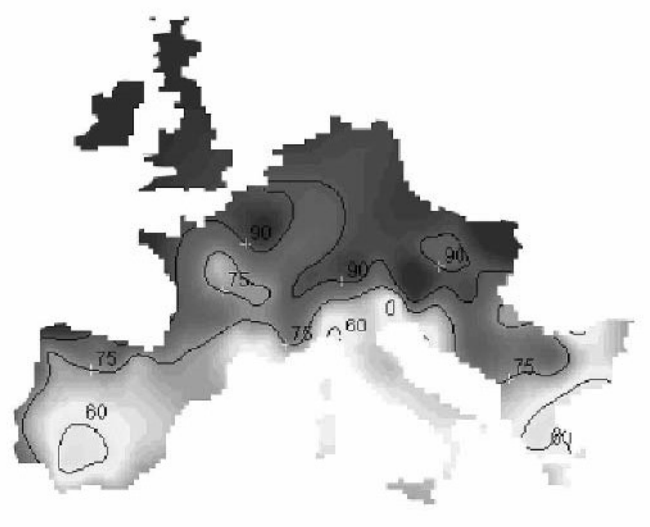
Chand (1973b), in his pioneering work, has studied the air motion produced by a ceiling fan and has concluded that:

- *the minimum clearance between the fan blades and the ceiling should be about 30cm;*
- *the capacity of a fan to meet the requirement of a room with a longer dimension L metres should be about 55 Lm^3/min; while*
- *the reduction of the ceiling height from 2.9m to 2.6m produces an increase in the air movement in the zone.*

Aynsley et al (1977) have provided air speed contours as generated by ceiling fans and concluded that effective air speeds are produced up to 1 fan blade diameter away from the centre of the fan.

Schmidt and Patterson (2001) have designed a new high-efficiency ceiling fan that can decrease the power consumption and, therefore, electricity charges by a factor of between two and three. A new very efficient ceiling fan of improved aerodynamics blades has been designed and tested by Parker et al (1999). The new ceiling fan presents a much higher airflow performance than existing fans and uses advanced control technology.

Finally, Wu (1989) has demonstrated the potential of oscillating fans to extend the comfort zone. In particular, for an air speed of 1.52m/sec, comfort is achieved at 31° C at 50 per cent relative humidity (RH), at 32° C at 39 per cent RH, or at 33° C at 30 per cent RH.



Source: Maldonado (1999)

Figure 8.9 *Percentage of hours in which the free cooling is applicable for the south zone of a reference building*

Free-cooling techniques

Free-cooling and economizer cycles can significantly contribute to reducing the cooling demand of buildings. Free cooling is a strategy that reduces or minimizes the cooling demands of a building by using an excess of ambient air when outdoor air temperatures are lower than indoors.

In free-cooling techniques, ventilation rates used are larger than those needed to meet the basic fresh air requirements of occupants and lower or equal to the supply airflow rates obtained for design conditions in every zone as a function of the design supply air temperature needed to meet peak cooling loads.

A full description of free-cooling techniques, as well as an assessment of the energy potential of free-cooling techniques for Europe, is given by Maldonado (1999) (see Figure 8.9). The design and details of free cooling are also described in ASHRAE (1980) and Perkins (1984).

Recently, Olsen et al (2003), have studied the performance of various low-energy cooling techniques coupled with a VAV and a displacement ventilation system for an office building in the UK. They found that the annual energy cost for displacement ventilation and VAV systems that use free cooling is about 20 per cent less than for the existing building, which uses a fixed minimum supply air rate that does not take advantage of free cooling.

Hybrid systems

Hybrid ventilation can be described as 'systems that provide a comfortable internal environment using both natural ventilation and mechanical systems but using different features of these systems at different times of the day or season of the year and within individual days' (Heiselberg, 2002). Compared to conventional ventilation systems, hybrid ventilation systems vary because they are based on an intelligent control system that permits switching between natural or mechanical modes in order to minimize energy consumption.

The main advantages of the hybrid ventilation systems are summarized by Heiselberg (2002):

- Hybrid ventilation results in higher user satisfaction as it permits a higher degree of individual control of the indoor climate.
- These systems optimize the balance between indoor air quality, thermal comfort, energy use and environmental impact and thus fulfil the needs for a better indoor environment and reduced energy consumption.

- Hybrid ventilation systems have access to natural and mechanical ventilation modes and exploit the benefits of each mode in the best way.
- These systems are also very appropriate solutions for complex buildings since they are associated with more intelligent systems and control.

Various hybrid ventilation systems have been proposed and applied in different types of buildings. An extended review of the systems, as well as of their existing applications, is provided by Delsante and Vik (2001). Olsen et al (2003) have also found that in the UK, while natural ventilation alone cannot maintain appropriate summer comfort conditions, the use of a hybrid system employing natural ventilation, together with a VAV system to maintain comfort during extreme periods, is the best choice, using at least 20 per cent less energy than any purely mechanical system.

Results from the first-generation hybrid-ventilated buildings show that such a technique has a very high cooling potential. It has been found that it is quite effective in providing good indoor air quality (IAQ) and thermal comfort, while energy performance is good, though requiring further improvements.

Summary

The energy consumption of buildings is high and is expected to increase further because of improved standards of living and the increase in world population During the last 20 years, air conditioning has presented a very high penetration rate and this has contributed significantly to increasing absolute energy consumption, as well as the peak electricity load of the building sector.

Convective cooling techniques have proven to be extremely energy efficient under specific climatic conditions. Extensive experimental and theoretical studies have shown that the application of convective cooling techniques may substantially reduce or neutralize the cooling load of buildings.

Over the last 20 years, important basic and industrial research has been carried out that has resulted in the development of new high-efficiency strategies, systems, control devices and tools. However, the continuing increase of energy consumption, primarily because of the important increase in air-conditioning installations, demands a more profound examination of convective cooling techniques and their impact upon buildings.

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